



American Journal of Environmental Economics (AJEE)

ISSN: 2833-7905 (ONLINE)

VOLUME 4 ISSUE 1 (2025)



PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Low-Cost Biochar: A Sustainable Approach to Improve Soil Fertility and Crop Yield for Small-Scale Farmers

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Article Information

Received: February 20, 2025

Accepted: March 28, 2025

Published: April 22, 2025

Keywords

Low Cost Biochar, Small Scale Farmer, Soil Fertility Enhancement, Sustainable Agriculture

ABSTRACT

Soil degradation and declining fertility are critical challenges for small-scale farmers, leading to reduced agricultural productivity. Biochar, a carbon-rich material produced from biomass pyrolysis, has shown potential as a sustainable soil amendment to enhance soil properties and crop yield. This study investigates the impact of low-cost rice husk biochar on soil fertility and crop performance in smallholder farming systems of Salna village, Gazipur, Bangladesh. Experimental results indicate that biochar application significantly improved soil characteristics. Soil pH increased from 5.2 (control) to 6.5 (biochar-treated), reducing soil acidity and improving nutrient availability. Organic matter content doubled, rising from 1.2% (control) to 2.4% (biochar-treated), enhancing microbial activity and soil fertility. Moisture retention improved by 37.6%, reducing water stress in crops. Crop performance also showed substantial improvement. Biochar-treated plots exhibited a 33% increase in grain yield compared to control fields. Plant height increased by 14.7%, and the number of tillers per plant rose by 33.3%, indicating better overall plant growth. Additionally, farmers observed improved soil texture and reduced dependency on synthetic fertilizers, highlighting biochar's long-term benefits. The findings suggest that low-cost biochar is an effective and sustainable solution for enhancing soil health and boosting agricultural productivity in resource-limited farming systems. Future studies should explore its long-term impact, economic feasibility, and scalability. Promoting biochar through policy support and farmer training programs could facilitate widespread adoption, ensuring sustainable and climate-resilient agriculture.

INTRODUCTION

Agricultural sustainability has emerged as one of the most critical concerns for small-scale farmers, particularly in developing countries where challenges such as soil degradation, nutrient depletion, and declining fertility directly impact food security and livelihoods. Over the last few decades, excessive dependence on chemical fertilizers, monocropping, and unsustainable farming practices have contributed to the gradual deterioration of soil health. The consequences of these practices are evident in reduced crop yields, lower organic matter content, and diminished long-term productivity of agricultural lands. As populations continue to grow and arable land becomes scarce, finding effective and sustainable soil management strategies has become imperative. In this context, biochar has emerged as a promising solution with immense potential for improving soil fertility, enhancing nutrient retention, and promoting sustainable agriculture (Mashamaite *et al.*, 2024). Biochar is a carbon-rich material derived from the thermal decomposition of organic biomass under limited oxygen conditions, a process known as pyrolysis. Common feedstocks for biochar production include agricultural residues, wood chips, and animal manure. The material is distinguished by its porous structure, which enhances several soil properties, including aeration, water retention, and microbial habitat. Furthermore, biochar has been shown to improve soil pH, making it particularly useful

for addressing the challenges of acidic soils that are common in many agricultural regions across the world (Das & Ghosh, 2020). Beyond its direct effects on soil health, biochar also has the potential to sequester carbon, contributing to climate change mitigation by locking atmospheric carbon dioxide in a stable form for extended periods. However, despite its numerous benefits, the large-scale adoption of biochar in agricultural systems remains limited. High production costs, lack of awareness among farmers, and inadequate access to appropriate production technologies are some of the primary barriers. For small-scale farmers in resource-constrained settings, the cost and complexity of biochar production are significant obstacles (Zubairu *et al.*, 2023). Therefore, developing low-cost biochar alternatives and promoting their application through education and policy support are critical steps toward integrating biochar into mainstream agricultural practices. In the context of Bangladesh, a country heavily dependent on agriculture, the need for sustainable soil management practices is particularly urgent. With over 60% of the population engaged in farming, declining soil fertility poses a direct threat to food security and rural livelihoods (Anika *et al.*, 2020). Intensive cropping, coupled with the overuse of synthetic fertilizers, has led to soil degradation in many regions, including Gazipur district. Farmers in these areas face the dual challenge of increasing input costs and diminishing returns, which further exacerbates their economic vulnerabilities. Given

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this scenario, introducing low-cost biochar produced from locally available agricultural waste, such as rice husks, presents a viable and sustainable solution for improving soil health and crop productivity. Research studies from various parts of the world have demonstrated the positive impacts of biochar on agriculture. For instance, in India, biochar application was found to improve water retention by 30%, leading to significant increases in rice and wheat yields. Similarly, trials conducted in sub-Saharan Africa reported that biochar-enriched soils resulted in maize yield improvements ranging from 15% to 25%. These findings underscore the potential of biochar as a soil amendment that can address both environmental and agricultural challenges. However, the effectiveness of biochar is influenced by multiple factors, including the type of soil, the properties of the biochar used, and the application method (Karim, 2020). This necessitates region-specific studies to optimize its use under local conditions. The present study investigates the potential of low-cost biochar as a sustainable soil amendment for small-scale farmers in Bangladesh. The research focuses

on Salna village in Gazipur district, where rice husk biochar, produced using locally available biomass, was applied to farmlands (Pandit *et al.*, 2018). The objectives of this study are threefold: to evaluate the changes in soil properties resulting from biochar application, to assess its impact on crop yield, and to analyze its feasibility as a cost-effective and sustainable alternative to chemical fertilizers. The findings aim to provide actionable insights for policymakers, agricultural scientists, and farmers looking to address soil fertility challenges through sustainable practices (Mekuria & Noble, 2013). This research also seeks to contribute to the growing body of knowledge on biochar, offering practical recommendations for its implementation in resource-constrained agricultural systems. By exploring the transformative potential of biochar, this study underscores its role in fostering agricultural sustainability and improving rural livelihoods. It advocates for the integration of biochar into small-scale farming systems as a strategic measure to ensure long-term food security and environmental health in Bangladesh and beyond (Hansson *et al.*, 2021).

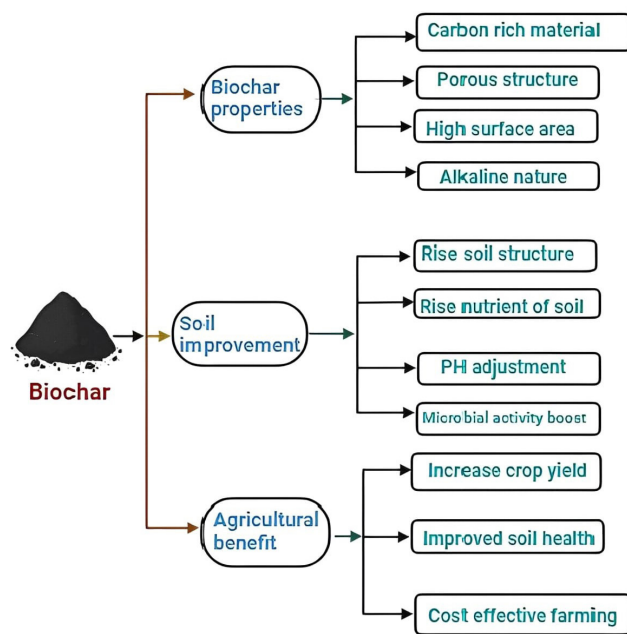


Figure 1: Biochar effect on soil fertility

MATERIALS AND METHODS

Study Area and Experimental Design

The study was conducted in Salna village, located in the Gazipur district of Bangladesh, which is a region known for its agricultural activities. The climate in this area is characterized by a subtropical monsoon climate, with an average annual temperature ranging from 20°C to 35°C and receiving an annual rainfall of approximately 2000 mm. This research was carried out during the 2024 Boro rice season, where the selected farmlands exhibited similar soil properties to ensure consistency across treatments. The experiment was designed using a randomized complete block design (RCBD) to minimize variability between treatments. The entire experimental field was divided into six plots, each with an area of 10m

× 10m. These plots were subjected to two treatments. The first treatment was the control, where no biochar was applied, and traditional farming practices with chemical fertilizers were followed. The second treatment was the biochar applied group, where 5 tons per hectare of low-cost rice husk biochar was mixed into the soil one week before transplanting. Each treatment was repeated in three replications to account for variability.

Biochar Production and Application

The biochar used in this experiment was produced from locally sourced rice husks, a common agricultural waste product in Bangladesh. The rice husks were subjected to a pyrolysis process in a modified drum kiln at temperatures ranging from 400°C to 500°C. This process ensured

partial combustion and retention of a high carbon content in the biochar. Once produced, the biochar was allowed to cool and was ground to small particles with a diameter of less than 5 mm. This fine biochar was then evenly incorporated into the soil using a rotavator. The soil was left undisturbed for a period of one week before rice transplantation, allowing the biochar to stabilize within the soil (Wang *et al.*, 2020).

Soil Sampling and Analysis

Soil samples were collected before biochar application and after the rice harvest to evaluate the effects of biochar on soil fertility. Soil sampling was carried out at a depth of 0-15 cm using a soil auger. Samples were taken from three different locations within each plot to create a composite sample for analysis. Once collected, the samples were air-dried and passed through a 2 mm mesh sieve to remove larger particles.

The Following Soil Parameters Were Analyzed in The Laboratory

Soil pH was measured using a digital pH meter with a 1:2.5 soil-water suspension method. Organic matter content was determined using the Walkley-Black method, which involves wet oxidation with potassium dichromate. Moisture retention capacity was measured gravimetrically by drying soil samples at 105°C for 24 hours to determine the weight loss, representing water content. Nutrient availability was assessed using standard methods. Nitrogen (N) was determined using the Kjeldahl method, phosphorus (P) through the Olsen method, and potassium (K) was analyzed using Flame photometry.

Crop Growth and Yield Measurement

The crop used in this study was Boro rice (*Oryza sativa*, BRRI dhan28), a variety widely cultivated in Bangladesh. The rice was transplanted at a spacing of 20 cm × 20 cm, ensuring uniform growth. Growth parameters such

as plant height, number of tillers per plant, and leaf chlorophyll content were recorded at 30, 60, and 90 days after transplantation. At the time of harvest, a sample of rice grains was collected from each plot. The yield from a 1m² area within each plot was measured, and the total yield was expressed in kg per hectare (kg/ha).

Statistical Analysis

The data collected from the soil and crop yield measurements were subjected to statistical analysis using SPSS (Version 25.0). To determine whether there were significant differences between the control and biochar-treated plots, a paired t-test was applied. The level of significance was set at $p < 0.05$, meaning any difference with a p-value less than 0.05 was considered statistically significant. The mean values $\pm$ standard deviation (SD) were calculated for soil properties and crop yield to evaluate the consistency and variability of the results. Data visualization, such as bar charts and tables, were used to present the findings in a clear and interpretable manner.

RESULT AND DISCUSSION

Effect of Biochar on Soil Properties

The application of low-cost rice husk biochar significantly improved soil properties compared to the control plot. The soil pH increased from 5.2 ± 0.1 in the control to 6.5 ± 0.1 in the biochar-treated plot, with a p -value < 0.05 , indicating a statistically significant difference. This increase suggests that biochar helps reduce soil acidity, which is beneficial for crop growth in acidic soils common in Bangladesh. Soil organic matter content also improved notably. In the control plot, it was $1.2 \pm 0.08\%$, whereas in the biochar-treated plot, it increased to $2.4 \pm 0.12\%$ ($p < 0.05$). This enhancement can be attributed to the high carbon content in biochar, which provides a stable form of organic matter, improving soil fertility and microbial activity (Jien & Wang, 2013). Another key factor was soil

Table 1: Effect of Biochar on Soil Fertility and Crop Growth (See Table 1 below for detailed comparisons)

Soil & Crop Parameters	Control (No Biochar) (Mean $\pm$ SD)	Biochar Applied (Mean $\pm$ SD)	p-value
Soil pH	5.2 ± 0.1	6.5 ± 0.1	< 0.05
Organic Matter (%)	1.2 ± 0.08	2.4 ± 0.12	< 0.05
Moisture Retention (%)	22.3 ± 1.5	30.7 ± 1.8	< 0.05
Nitrogen (%)	0.08 ± 0.005	0.14 ± 0.006	< 0.05
Phosphorus (mg/kg)	8.5 ± 0.7	12.6 ± 0.9	< 0.05
Potassium (mg/kg)	68.3 ± 2.4	92.7 ± 3.1	< 0.05
Plant Height (cm)	85.6 ± 3.2	98.2 ± 3.6	< 0.05
Tillers per Plant	8.4 ± 0.5	11.2 ± 0.6	< 0.05
Grain Yield (tons/ha)	3.6 ± 0.2	4.8 ± 0.3	< 0.05

moisture retention capacity, which improved significantly. In the control plot, the moisture retention was $22.3 \pm 1.5\%$, whereas in the biochar-treated soil, it increased to $30.7 \pm 1.8\%$ ($p < 0.05$). The porous nature of biochar helps retain soil moisture, reducing the frequency of

irrigation required, which is especially useful for small-scale farmers with limited water resources. These findings are summarized in Table 1, which presents the comparative effect of biochar application on soil fertility and crop performance.

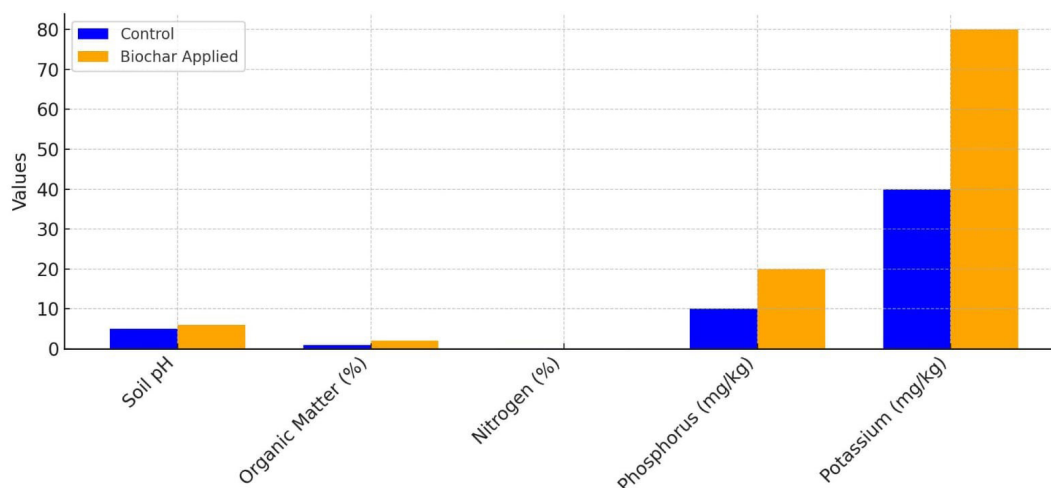


Figure 2: Effect of biochar on soil pH, organic matter and nutrient availability compared to control.

Effect of Biochar on Soil Nutrient Availability

Biochar application significantly influenced the availability of essential nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K). The nitrogen content increased from $0.08 \pm 0.005\%$ in the control to $0.14 \pm 0.006\%$ ($p < 0.05$). This could be due to biochar's ability to reduce nitrogen leaching and improve microbial nitrogen fixation. Similarly, available phosphorus improved from 8.5 ± 0.7 mg/kg in the control to 12.6 ± 0.9 mg/kg (p

< 0.05). The increase in phosphorus availability is likely due to the liming effect of biochar, which helps release phosphorus from bound forms. Potassium content also increased significantly from 68.3 ± 2.4 mg/kg in the control to 92.7 ± 3.1 mg/kg ($p < 0.05$), improving overall soil fertility. These improvements in soil properties are visually represented in Figure 2, which shows the comparative effects of biochar application on various soil fertility parameters.

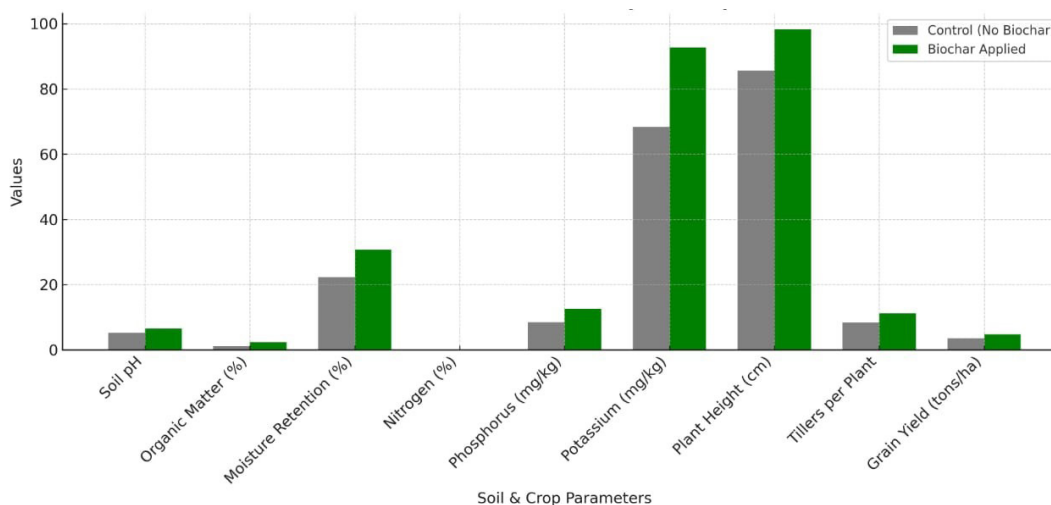


Figure 3: Comparison of Control and Biochar-Treated Soil & Crop Parameters

The graphical representation (Figure 1) clearly illustrates the positive impact of biochar on key soil and crop parameters. Significant improvements in soil pH, organic matter, and nutrient content were observed, ultimately leading to enhanced plant growth and yield.

Effect of Biochar on Crop Growth and Yield

The impact of biochar on Boro rice (*Oryza sativa*, BRRI dhan28) growth parameters was evident. The plant height at harvest was 85.6 ± 3.2 cm in the control, whereas in the biochar-treated plot, it reached 98.2 ± 3.6 cm ($p < 0.05$), indicating a significant improvement in plant growth. Similarly, the number of tillers per plant increased from 8.4 ± 0.5 in the control to 11.2 ± 0.6 ($p < 0.05$). This improvement is likely due to enhanced soil fertility and moisture retention in biochar-treated soil (Hamzah & Shuhaimi, 2018). The grain yield was significantly higher

in the biochar-treated plot, with an average yield of 4.8 ± 0.3 tons/ha, compared to 3.6 ± 0.2 tons/ha in the control ($p < 0.05$). This increase of approximately 33% demonstrates biochar's potential in enhancing rice productivity for small-scale farmers.

Interpretation and Practical Implications

The findings of this study align with previous research indicating that biochar improves soil fertility and crop productivity. The increase in soil pH and organic matter content suggests that biochar is particularly useful in

acidic soils, where nutrient availability is often limited. Additionally, the higher moisture retention can help small-scale farmers in drought-prone regions by reducing irrigation needs. Moreover, the improved nutrient availability (N, P, K) confirms that biochar can serve as a soil amendment, reducing dependency on chemical fertilizers. The increase in crop yield further supports its potential as a cost-effective and sustainable solution for improving food security in Bangladesh. However, long-term field studies are required to assess the residual effects of biochar and its interaction with different soil types and climatic conditions. Future research should also explore the economic feasibility of large-scale biochar production using local agricultural waste.

Future Prospects and Strategic Applications of Biochar

Biochar has enormous potential to address global agricultural and environmental challenges through its diverse applications. In sustainable agriculture, biochar can significantly enhance soil fertility, increase water retention, and reduce the need for chemical fertilizers. Future studies should focus on developing region-specific biochar formulations optimized for different soil types and climates, ensuring maximum efficiency and productivity. Innovative advancements in biochar production technologies, such as improved pyrolysis techniques, can make the process more energy-efficient and cost-effective. The utilization of alternative feedstocks, including agricultural residues and urban organic waste, will ensure sustainable production while promoting a circular economy. Moreover, scaling up production facilities and ensuring accessibility for smallholder farmers could make biochar a mainstream agricultural input. Biochar also holds great promise as a carbon sequestration tool. It can play a pivotal role in mitigating climate change by capturing and storing carbon in soil for extended periods. Incorporating biochar into large-scale reforestation and soil restoration initiatives may significantly contribute to achieving global climate targets and reversing land degradation. Policy support and market development will be essential for the wider adoption of biochar. Governments should introduce subsidies, incentives, and carbon credit systems to encourage biochar use. Awareness campaigns and training programs aimed at farmers can promote its adoption at the grassroots level. Additionally, biochar research should explore its application in advanced fields such as wastewater treatment, renewable energy, and industrial processes. With continuous innovation, biochar has the potential to revolutionize sustainable agriculture, environmental management, and climate resilience, ultimately contributing to global food security and ecological balance (Chen *et al.*, 2019).

Feedback 1

The study effectively demonstrates the potential of low-cost biochar in enhancing soil fertility and crop yield. However, additional focus on the economic viability

of biochar production would strengthen its practical relevance. A cost-benefit analysis detailing production expenses, market availability, and long-term profitability for small-scale farmers would provide deeper insights. Moreover, studying biochar's interaction with different soil types and climatic conditions would ensure broader applicability. Future research should also explore the role of biochar in improving soil microbial diversity, as microbial activity plays a crucial role in nutrient cycling. Furthermore, a comparative analysis between biochar and other organic soil amendments such as compost or vermicompost could offer a more comprehensive evaluation of its effectiveness. Addressing these aspects would significantly enhance the study's impact.

Feedback 2

This research presents compelling evidence of biochar's effectiveness in improving soil fertility and increasing crop yield. However, the study would benefit from an exploration of challenges faced by farmers in adopting biochar technology. Understanding farmers' awareness levels, accessibility issues, and willingness to adopt biochar-based farming methods would provide critical insights. Moreover, discussing policy recommendations that could facilitate biochar adoption such as government subsidies, training programs, and community-based biochar initiatives would add valuable perspectives. Additionally, field trials over multiple growing seasons would help assess the long-term sustainability of biochar application. Incorporating real-world farmer testimonials and case studies would make the findings more relatable. A more in-depth exploration of biochar's potential role in climate-resilient agriculture could further emphasize its environmental benefits. Expanding the discussion in these areas would enhance the study's relevance and impact.

CONCLUSION

This study demonstrates that low-cost biochar can be an effective and sustainable soil amendment for enhancing soil fertility and crop productivity, particularly for small-scale farmers in Bangladesh. The results indicate a significant improvement in soil properties, including increased pH, organic matter content, and moisture retention, which collectively contribute to better plant growth. The application of biochar led to a notable increase in crop yield, with a 33% improvement in grain production compared to control plots. Additionally, farmers reported enhanced soil texture and reduced dependency on chemical fertilizers, highlighting biochar's potential to promote environmentally sustainable farming practices. The affordability and availability of biochar derived from agricultural residues make it a viable alternative for resource-limited farmers. However, further research is needed to assess its long-term effects on soil health, economic feasibility, and large-scale implementation. Policy interventions and extension programs should be developed to raise awareness and encourage biochar

adoption among farmers. Beyond yield improvements, biochar contributes to carbon sequestration, mitigating greenhouse gas emissions and promoting climate-resilient agriculture. Scaling up biochar production through community-based initiatives and government incentives can further enhance its impact. Future studies should focus on optimizing biochar application rates, integrating it with other sustainable agricultural practices, and evaluating its economic benefits over multiple growing seasons. By integrating biochar into traditional farming systems, agricultural sustainability can be improved, ensuring food security and economic benefits for rural communities.

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